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West Point, New York 10996

An Agent-Based Modeling Approach to Quantifying the Value of Battlefield Information

OPERATIONS RESEARCH CENTER OF EXCELLENCE
TECHNICAL REPORT # DSE-TR-02-11
DTIC #: ADAXXXXX

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Center for Army Analysis
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TRADOC Analysis Center, White Sands Missile Range

Senior Investigator
Colonel William B. Carlton, Ph.D.
Academy Professor, Department of Systems Engineering

Directed by
Colonel Bill Klimack, Ph.D.
Director, Operations Research Center of Excellence

Approved by
Colonel Michael L. McGinnis, Ph.D.
Professor and Head, Department of Systems Engineering

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Abstract

For several years the U.S. Army and Department of Defense have struggled with how to measure the value of battlefield information. Digital information systems have demonstrated the potential to significantly increase the combat effectiveness of our forces, but in order to make procurement, force structure, and basis of issue decisions, we would like to gauge the extent to which these systems increase combat effectiveness. This paper describes a methodology we chose to investigate whether an agent-based-model (ABM) could be used to suggest appropriate behaviors for a combat force equipped with a proposed information system such as Future Battle Command Brigade and Below – FBCB2. The decision agents within the model will use the information about enemy forces, friendly forces, and terrain provided by the proposed information system to adjust the friendly course of action to the updated situation. Our methodology is a three-step process. We first execute simulation runs using an existing dynamic study scenario and evaluate the results of these runs. In the second step, we transfer the terrain, units, and course of action from the existing dynamic scenario to an ABM with intelligent agents that will refine the course of action by generating new unit positions and routes based upon the current situation. In the final step, we substitute the ABM developed course of action and behaviors back into the dynamic study scenario and execute another set of simulation runs. The performance of the friendly force using the proposed information system and ABM generated behaviors may be compared to the performance of the friendly force which failed to take advantage of current information. This gives insight into the potential increase in combat effectiveness realized through the use of an information system.

Acknowledgements

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Introduction

Despite increased investments in military tactical information systems, the analysis community has great difficulty in quantifying the contribution of these systems to the overall fight, in answering the question, "How much is a pound of C4ISR worth?" The Army's Objective Force Maneuver Unit of Action (UA) intends to further increase its information advantage, "Able to *see first and understand first* with combat information on terrain and weather, Red and Blue forces and noncombatants tailored to unit task and purpose, the UA will develop the situation, out of contact, and establish a dynamic tactical information sphere in order to determine when and where to fight on favorable terms."[1] However, the Military Operations Research Society Workshop on Advancing C4ISR Assessment concludes that analysis of major combat operations would benefit from improved modeling tools for command and control, for behavior modeling, and for assessing the contribution of C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance) relative to weapons.[2]

This paper proposes agent-based modeling as a methodology that allows the military analyst to quantify the value of information as follows, "The value of combat information to A Company, if they act upon it, is a 380% increase in enemy losses with no significant change in friendly losses." To be more specific, the networked C4ISR systems available to A Company in the given scenario allowed them to destroy 3.8 times more targets with no significant change in friendly losses.

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[1] TRADOC Pamphlet 525-3-90, "Objective Force Maneuver Units of Action," United States Army Training and Doctrine Command, 1 November 2002.

[2] Cy Staniec, Stuart Starr, and Charles Taylor, "MORS Workshop on Advancing C4ISR Assessment," *Phanlanx,* volume 34, number 1, March 2001.

Agent-based modeling fills a critical gap in military modeling capabilities, the ability to model how a combat soldier makes a tactical decision. That decision leads to a tactical action that allows that soldier to leverage the value of information. This paper first identifies the existing gap in modeling capabilities. It then introduces agent-based modeling as a technical approach to filling that gap. It then presents two tactical decision making agents, the position agent and the route agent, as examples. These agents use information available to combat units in order to allow them to seek a position of advantage as they maneuver through complex terrain and enemy fire toward an objective. In an experimental scenario, routes generated by these agents, when evaluated in a high-resolution combat model, led to a significantly better mission performance. That mission performance improvement is the quantifiable value of battlefield information.

A Gap in Modeling Capabilities

An assessment of existing modeling capabilities identifies a critical gap in the ability to quantify the effects of an information gain, as shown by the knowledge hierarchy in figure 1. At the lower end of the pyramid, existing combat models represent the physical effects of target acquisition and the dissemination of its reports across the battlefield. At the top of the pyramid, combat models simulate the combat effects of tactical action as it relates to attrition and control of terrain on the tactical battlefield. The gap is in the middle. The largely human process that translates battlefield information collected by C4ISR systems into decisions which organize and direct battlefield systems to gain a position of tactical advantage in order to accomplish friendly missions is not well modeled. This decision-making process brings value to the networked force. The information on the network has little intrinsic value. It is only valuable to the extent to which it allows decision-makers to direct tactical forces on the battlefield to better accomplish

the unit's mission. Embedding decision agents in combat models is one technical approach to filling this modeling gap in order to better quantify the value of network-centric capabilities.
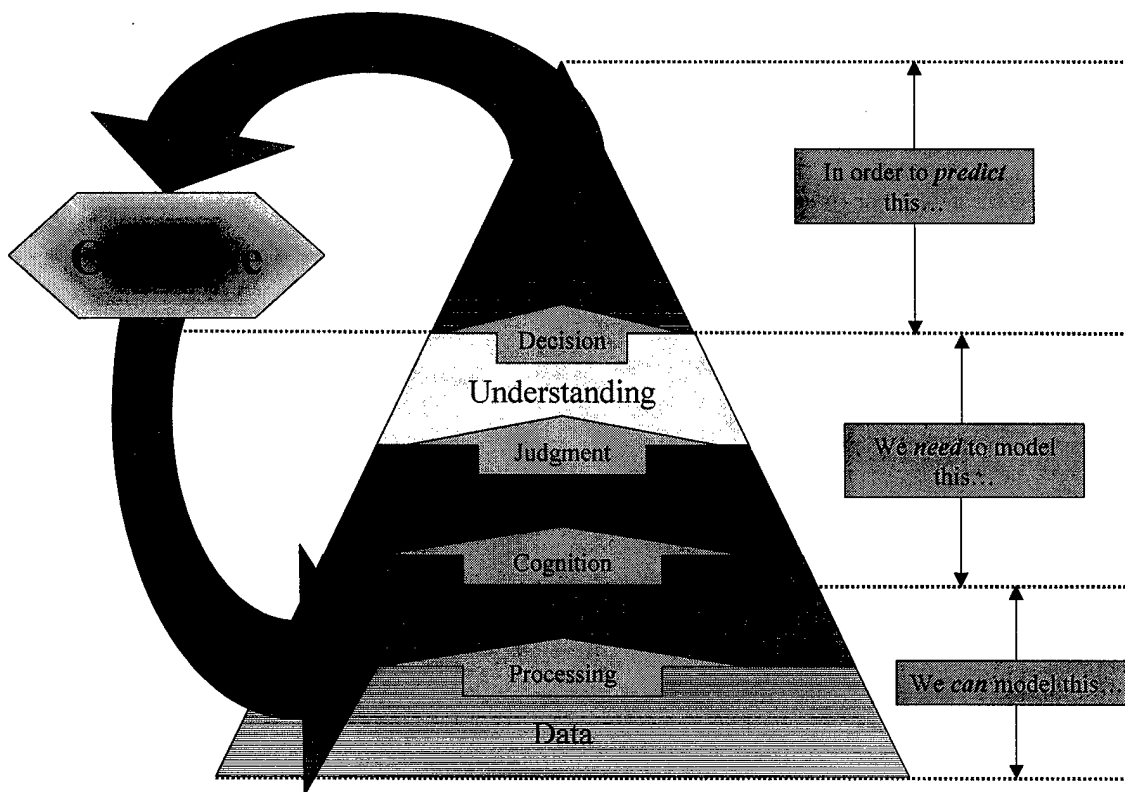
Figure 1. Combat models are able to model the effects of collecting data and information (bottom of the pyramid) and the effects of tactical actions (top of the pyramid). The gap is in the middle where models have trouble translating the information collected into knowledge and understanding which allow a tactical decision to take a different action.

Agent-Based Modeling

Agents are programmed software modules that scan their environment and make a decision.[3] In a military context, these decisions may be local decisions, such as moving one vehicle to avoid incoming fire, or global decisions such as the allocation of fire missions to a suite of shooters in order to engage the known set of targets. An agent-based model is one in

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[3] Andrew Ilachinski, *Land Warfare and Complexity, Part I: Mathematical Background and Technical Sourcebook,* Alexandria, VA: Center for Naval Analysis, July 1996, pp. 101-102.

which the connections and interactions among the agents has significant effects, as compared to the individual actions of any particular agent. These interactions give rise to emergent properties. In a complex system, emergent properties are those trends that, although not explicitly modeled, consistently arise out of the interactions between agents. Agent based models are designed not as much to predict detailed outcomes as to gain insights and understanding of the system.[4] The increased capability of network-centric forces, if it really exists, is an emergent property. It cannot be proven with attrition-based equations of combat. However, in an agent-based model, a large number of unit agents use network connectivity to enhance their ability to interact with each other and the environment. If greater combat capability emerges consistently from these improved interactions, then analysts can gain some analytical insight about the potential combat capability of network-centric forces.

Supporting Research

This paper represents a cross-fertilization and extension of two separate research projects at the United States Military Academy (USMA) Department of Systems Engineering. The Irreducible Semi-Autonomous Adaptive Combat (ISAAC) system is a well-documented agent-based model of greatly simplified land combat.[5] USMA Department of Systems Engineering researchers conducted a study using ISAAC to better quantify C4ISR effects on a simplified battlefield. Their research showed an improved performance of information-enabled forces, particularly if those forces were able to adapt their tactics to take better advantage of the

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[4] Ibid, pp. 100-103.

[5] Andrew Ilachinski, 2000. Irreducible semi-autonomous adaptive combat: An artificial life approach to land combat. *Military Operations Research*, 5(3): 27-46.

improved information flow.[6] In another USMA experiment, adaptive decision-agents in the Combat Operations Support System for Adaptive Command and Control (COSSACC) developed an operations order, modified tactical routes, and adjusted positions of tactical forces to better attain higher-level objectives.[7] These agents, when used for decision support, improved the performance of the force in a detailed combat simulation. A natural next step was to combine the methods of these two projects using an accredited simulation system.

JCombat – An Agent-Based Combat Model in Java

In order to integrate agents from the COSSACC system into a more detailed simulation model, this project's analysts developed JCombat, a high-resolution, moderately-detailed, but fast-running combat simulation written in Java. JCombat exists as a test bed for command and control agents for potential integration into even more detailed accredited simulation models. It contains a detailed terrain model and line of sight algorithms. It handles direct fire in great detail. However, programming time constraints and an interest in execution speed forced a more abstract representation of target acquisition, communications, and intelligence processes. In this initial experiment, there was no representation of indirect fires.

The JCombat simulation contains enough detail to allow the friendly force to receive a set of spot reports, build a partial common operational picture for the friendly force, and disseminate that picture to subordinate units for decision-making. This common operational picture, along with some friendly objectives, was used by each unit in the friendly force to continuously update

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[6] Larry Larimer and William B. Carlton. "Using Complex Adaptive System Theory and Agent Based Modeling to Quantify the Value of Battlefield Information." Presentation delivered at INFORMS Military Applications Society International Meeting, May 2001.

[7] Robert Kewley and Mark Embrechts. "A Multiagent System For Tactical Control Of Automated Forces." Unpublished manuscript submitted to *Military Operations Research,* November 2001.

its routes and positions during the fight to seek a position of advantage and better accomplish unit missions. Two decision agents performed these tasks, the position agent and the route agent.

An operations order in JCombat may, instead of specifying an explicit route for a unit, give the unit a movement technique and allow the route agent to generate the unit's route. This movement technique defines the objectives a unit should seek as it develops its route. For example, the assault movement technique seeks speed and enemy destruction, while the recon technique seeks enemy acquisition as opposed to destruction, with little emphasis on speed. This is accomplished by a linear value model which assigns weights to the individual tactical characteristics of the route. The route evaluation model determines the average friendly rate of attrition against known enemy encountered along the route, the average enemy rate of attrition against the friendly unit as it traverses the route, the average number of enemy vehicles seen while traversing the route, and the total time required to reach the end of the route. For an assault, the value model assigns a weight of 100 to attriting the enemy, 80 to avoiding attrition, 30 to finding the enemy, and 40 to minimizing time. For a recon movement technique, the value model assigns a weight of 10 to attriting the enemy, 100 to avoiding attrition, 100 to finding the enemy, and 10 to minimizing time. These weights may be adjusted by the analyst to represent different value scores for different movement techniques.

A genetic algorithm evolves successive populations of routes for evaluation by the route evaluation model. The route planning genetic algorithm used by the route selection agent was adapted from the works of Hocaoglu and Sanderson[8] and Xiao et. al.[9] The genetic algorithm

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[8] Cem Hocaoglu and Arthur C. Sanderson." Multimodal function optimization using minimal representation size clustering and its application to planning multipaths." *Evolutionary Computation*, 5(1):81-104, 1997.

[9] Jing Xiao, Zbigniew Michalwicz, Lixin Zhang, and Krzysztof Trojanowski. Adaptive evolutionary planner/navigator for mobile robots. *IEEE Transactions on Evolutionary Computation*, 1(1):18-28.

represents a route as a variable length list of points through which a unit must pass while moving from its current destination to its final destination. Each point is an x,y coordinate pair in the continuous domain. In this representation, a unit's route may have from zero (move straight to destination) to any number of waypoints evolved by the algorithm. The algorithm adds a point to a route by inserting a knot point along one of the route legs. The point insertion algorithm first chooses one of the route legs at random. In figure 2, the algorithm has randomly selected leg 2 from the three possible route legs. It then randomly chooses an interim point along that leg at which it will insert the knot point. It then must determine a knot distance. The knot distance is a random value drawn from a normal distribution with a mean of zero and a standard deviation of 1/2 the length of leg 2. If the knot distance is positive, then a knot point is inserted perpendicularly to one side of the leg. If the knot distance is negative, the knot point is inserted perpendicularly to the other side of the leg. In figure 2, the knot point has been inserted perpendicular to leg 2 and knot distance from the interim point. The knot point is inserted in the route between points 1 and 2 to give a new route shown by the dotted line.
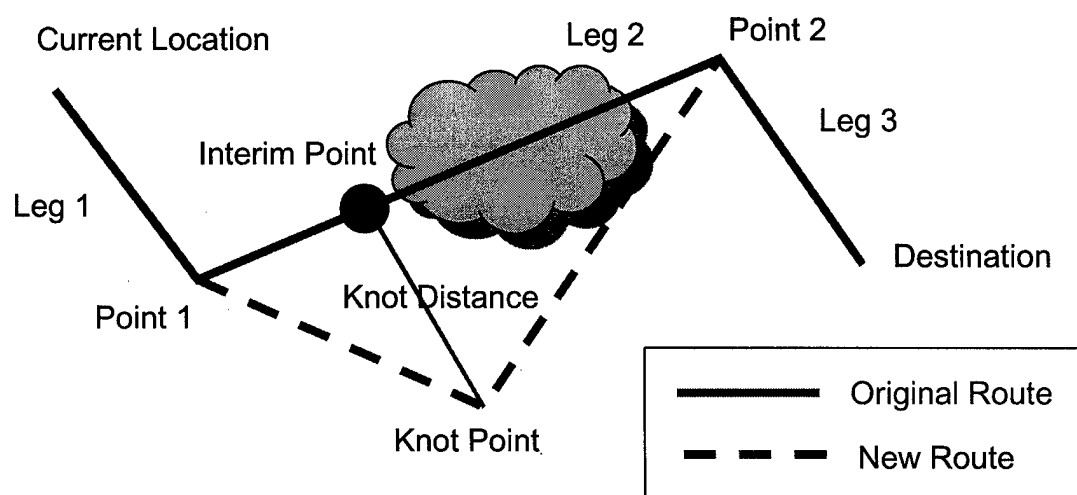

Figure 2. The process of adding a random point to a route. The knot point is inserted between points 1 and 2 to generate the new route shown by the dotted line.

Upon initialization, the route genome draws the initial number of points from a truncated exponential distribution with a mean of 1. It is most likely to have 0 points, next most likely to have 1 point, and so forth. For all initial points, the genome adds a random point to the route using the algorithm shown in figure 2. Upon crossover, two routes will perform single point crossover in order to form two offspring for the next generation. Upon mutation, the route genome will successively test each of its points for mutation. If a mutation trial is successful, one of three things will happen to the point, each with equal probability. The genome may remove the mutated point, the genome may add a random point to the route, or the genome may remove the mutated point and add a random point to the route. As a unit moves, the route selection agent re-evaluates its current route at fixed time intervals. If the genetic algorithm finds a better route, it will replace the current route. This allows a unit to adjust to the changing enemy situation as it moves.

A unit may adjust not only its route, but also its final destination, bounded by the flexibility distance given by the planning agent. In a manner similar to the one used by the route selection agent to evaluate routes for a given movement technique, the positioning agent evaluates candidate positions for a mission given by the planning agent - attack by fire, support by fire, defend, recon, delay, or hide. A mission is a set of objectives sought by the unit when it reaches its destination. For example, both the attack by fire and support by fire missions seek enemy destruction. However, the support by fire mission also places greater emphasis on staying close to the location given by the planning agent, so that it does not get too far away from the unit whose movement it supports. Since the search for a single position is a much simpler search task than the search for a route, the positioning agent uses a simple uniform random search as opposed to a genetic algorithm. At constant intervals, the agent uniformly selects a set of

random points from within a circle (see figure 3). The center and radius of the circle are determined by the location and flexibility distance given to the unit in its initial orders. A position evaluation model takes into account the surrounding terrain and enemy forces to give estimates for percentage of enemy units acquired, expected number of enemy vehicles destroyed, and expected number of friendly vehicles destroyed from each selected location. It also considers the distance from its assigned location. Based on its mission, the agent aggregates these criteria using a linear weighted value system to get an overall score for each location. This position value model is similar to the route value model used by the route agent. The agent will order the unit to reposition to the best location found.
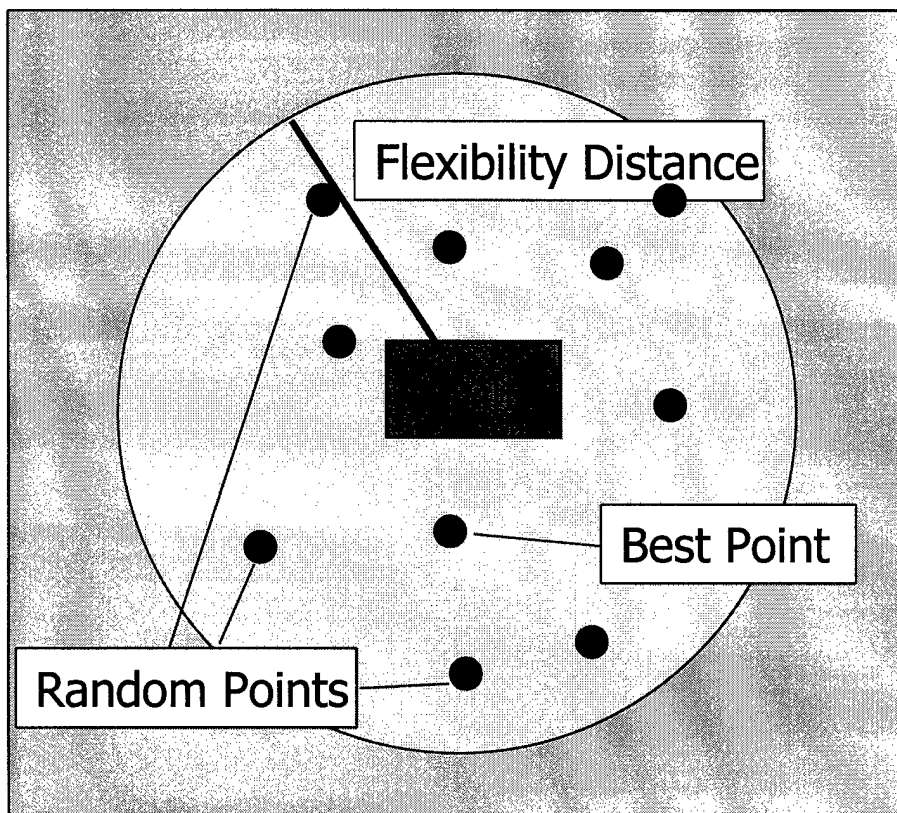

Figure 3. The process of selecting a new location. The evaluation model evaluates number of uniformly distributed random points within the flexibility distance. The position agent then moves the unit to the best point.

By these techniques JCombat runs were able to generate potential improvements in the routes and positions occupied by forces during a battle. Using the route agent and the position agent, this model filled the middle gap in the knowledge hierarchy in order to translate the information in the common operational picture into tactical decision to change the routes and positions units used during the run in order to better accomplish their assigned missions.

Value of Information Experiment

In order to quantify the value added to the force by the information-enabled tactical decision agents, analysts designed an experiment to evaluate the results of JCombat agent-based runs in a high resolution combat model. This experiment used a simple scenario in the Combined Arms Support Task Force Evaluation Model (CASTFOREM). In this scenario, an allied tank-heavy company-team had to attack across a valley to destroy elements of a defending enemy company. Prior to the attack, two unmanned aerial vehicles and a scout platoon conduct a reconnaissance to determine the disposition of enemy forces (see figure 4). The first step was to synchronize the scenario between JCombat and CASTFOREM (see figure 5). Analysts then evaluated the base case using a static course of action in the CASTFOREM scenario. For different treatments, routes generated by offline JCombat runs provided inputs to "agent-enabled" runs (see figure 6). It is important to note that any qualitative judgment about the tactical soundness of the agent-based routes can only be gained from observation. These quantitative agents are not capable of explaining themselves in tactical terms. Analysts compared the results of the static runs to the agent-enabled runs in order to quantify the value of information-enabled decision making.
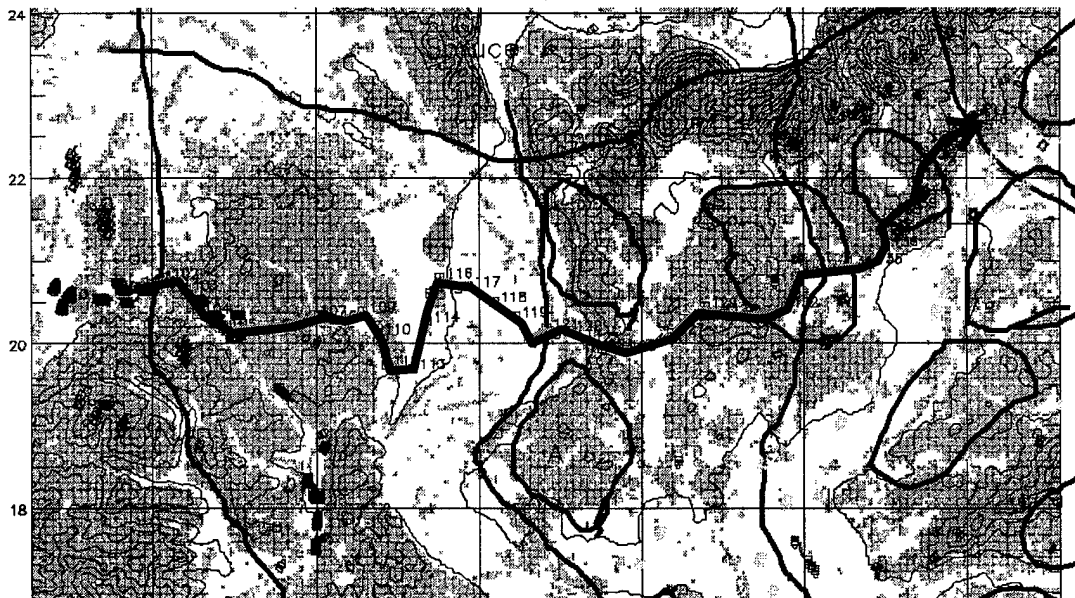
Figure 4. Experimental Scenario – CASTFOREM Screenshot. Elements of an allied tank-heavy company-team (left) must cross a valley and attack to destroy dispersed and well-hidden elements of a defending enemy force (right). In the base case, allied forces attacked in formation using the pre-scripted route shown here.

Figure 5. Experimental Scenario – JCombat Screenshot. This JCombat scenario has been synchronized with terrain, unit positions, and routes from the CASTFOREM scenario in Figure 4.

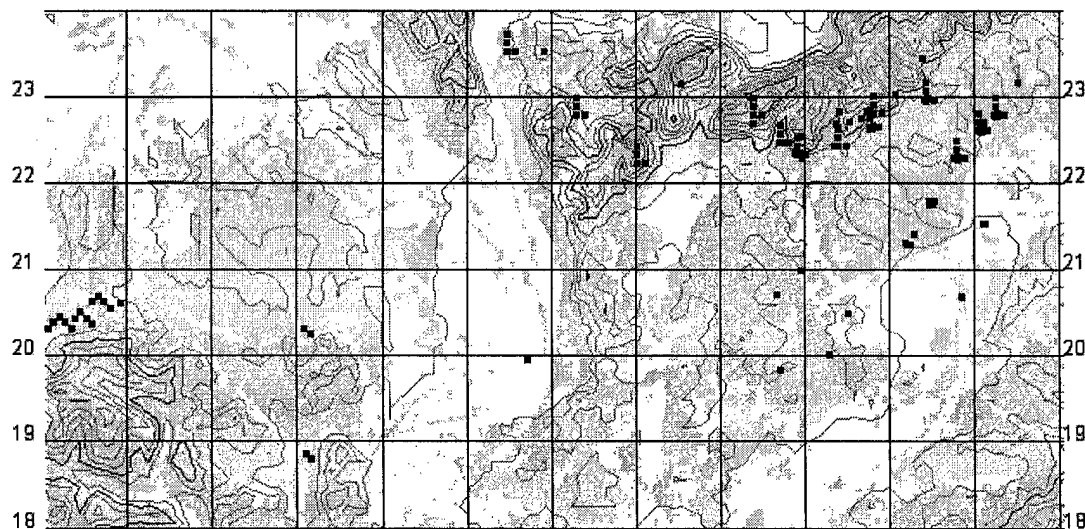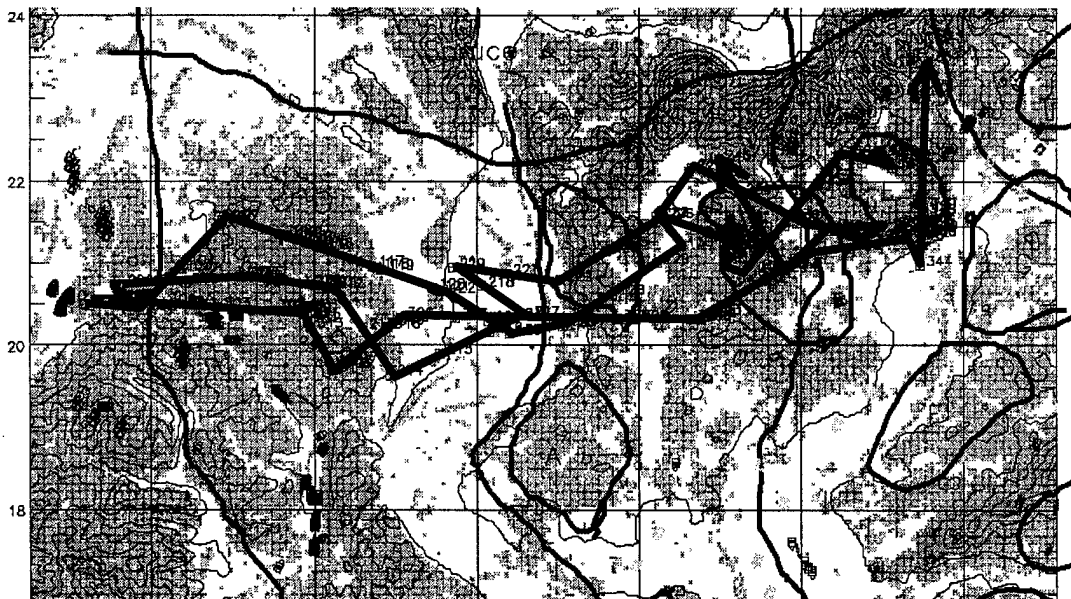Figure 6. Agent-Based Routes. The position agent and route agent in JCombat generated the routes shown here for evaluation in CASTFOREM. Note that the agent-enabled routes, while generally seeking covered and concealed movement, took more risk by occasionally darting closer to the mountains to engage enemy forces from positions of advantage.

Table 1 shows the number of losses for each side during the CASTFOREM runs. The runs are ranked by number of losses to support non-parametric statistical analysis of the difference between the two treatments. Note the preponderance of high attrition for red occurred during the agent-enabled runs. Using the Wilcoxon Rank-Sum test for differences in means,[10] this difference in enemy losses was statistically significant at the 0.008 level. There was no statistical difference in friendly losses between these treatments. Figure 7 is a graphical depiction of these results. The agent-enabled forces showed a 380% increase in enemy losses with a slight but statistically insignificant decrease in friendly losses. This sort of increase in mission effectiveness, with no increase in risk to friendly forces, represents the blue force's capability to transform information, via tactical decisions, into combat advantage.

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[10] Devore, Jay L. *Probability and Statistics for Engineering and the Sciences.* Brooks/Cole, 1995.

Red Losses		
Losses	Run	Rank
0	Base	1.5
0	Base	1.5
1	Base	4
1	Base	4
1	Agents	4
3	Base	6
4	Agents	7.5
4	Agents	7.5
5	Agents	9.5
5	Agents	9.5

Blue Losses		
Losses	Run	Rank
3	Base	1
4	Agents	2
4	Agents	3
5	Base	4
5	Agents	5
5	Agents	6
6	Base	7
6	Base	8
6	Agents	9
7	Base	10

Table 1. These tables rank the number of losses for enemy (red) and friendly (blue) losses in the ten CASTFOREM runs. The agent-enabled runs showed a statistically significant increase in red losses with no statistically significant difference in blue losses.
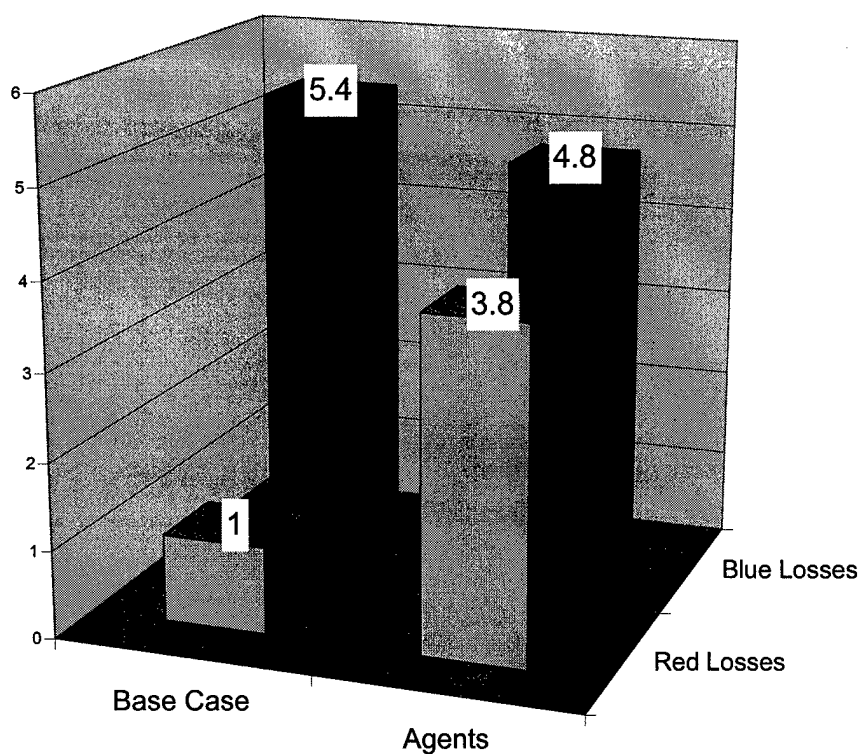

Figure 7. Mean performance of forces from 5 CASTFOREM runs for each of the two treatments. The agent-enabled forces destroyed 3.8 times more enemy forces with no significant difference in friendly losses.

Conclusions

Agent-based modeling has demonstrated an ability to quantify the value of tactical information. In a small scale tactical simulation, the position agent and the route agent serve as proxies for human decision makers. They translated situation awareness information about the enemy and the terrain into tactical decisions which provided a combat advantage. They are the key technology to fill a critical gap in modeling capability, the ability to translate battlefield information into actionable decisions which affect the outcome of the battle. In this particular case, the available situation awareness information and resulting actions yielded a significant increase in the ability to destroy enemy forces on the tactical objective without sacrificing survivability.

Agent-based modeling has great potential applicability in the analysis of C4ISR systems. Since these systems themselves don't attack targets or seize and hold terrain, their value added to the tactical unit is difficult to quantify when compared to other alternatives such as more forces or improved weapons. The first step would be to develop a suite of low-level tactical agents with capabilities similar to the route agent and the position agent. Different agents are necessary to perform different tactical decision making functions. Next, these agents should be integrated into an existing high-resolution combat model where they can make decisions based on the simulated situation awareness available to different units. This technical approach would provide an analysis tool capable of measuring, with comparable measures of mission performance, the value added of C4ISR systems and weapons systems. Such an analysis tool would have great potential to inform force design decision makers as they seek to provide the proper mix of soldiers, weapons, and information systems to current and future combat units.

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Appendix A: List of Abbreviations

A	
ABM	Agent Based Model
C	Combat Operations Support System for Adaptive Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconaissance
COSSACC	
CASTFOREM	Combined Arms Support Task Force Evaluation Model
D	
DTIC	Defense Technical Information Center
F	
FBCB2	Future Battle Command, Brigade and Below
I	The Irreducible Semi-Autonomous Adaptive Combat
ISAAC	Military Operations in Urban Terrain
O	
ORCEN	Operations Research Center
U	
UA	Unit of Action
USMA	United States Military Academy

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14. ABSTRACT

This paper describes a methodology we chose to investigate whether an agent-based-model (ABM) could be used to suggest appropriate behaviors for a combat force equipped with a proposed information system. The decision agents within the model will use the information about enemy forces, friendly forces, and terrain provided by the proposed information system to adjust the friendly course of action to the updated situation. We first execute simulation runs using an existing scenario. We then transfer existing scenario to an ABM with intelligent agents that will refine the course of action by generating new unit positions and routes based upon the current situation. In the final step, we substitute the ABM developed course of action and behaviors back into scenario and execute another set of simulation runs. The performance of the friendly force using the proposed information system and ABM generated behaviors may be compared to the performance of the base case. This gives insight into the potential increase in combat effectiveness realized through the use of an information system.

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